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Modern Control Systems Analysis and Design

Using MATLAB and Simulink

现代控制系统分析与设计

——应用MATLAB和Simulink

Robert H. Bishop

Pearson Education

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MODERN CONTROL SYSTEMS ANALYSIS AND DESIGN USING MATLAB AND SIMULINK

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出 版 说 明

郑大钟
清华大学信息科学与技术学院

当前，在我国的高等学校中，教学内容和课程体系的改革已经成为教学改革中的一个非常突出的问题，而为数不少的课程教材中普遍存在的“课程体系老化，内容落伍时代，本研层次不清”的现象又是其中的急需改变的一个重要方面。同时，随着科教兴国方针的贯彻落实，要求我们进一步转变观念扩大视野，使教学过程适应以信息技术为先导的技术革命和我国社会主义市场经济体制的需要，加快教学过程的国际化进程。在这方面，系统地研究和借鉴国外知名大学的相关教材，将会对推进我们的课程改革和推进我国大学教学的国际化进程，乃至对我们一些重点大学建设国际一流大学的努力，都将具有重要的借鉴推动作用。正是基于这种背景，我们决定在国内推出信息技术学科和电气工程学科国外知名大学原版系列教材。

本系列教材的组编将遵循如下的几点基本原则。(1)书目的范围限于信息技术学科和电气工程学科所属专业的技术基础课和主要的专业课。(2)教材的范围选自于具有较大影响且为国外知名大学所采用的教材。(3)教材属于在近 5 年内所出版的新书或新版书。(4)教材适合于作为我国大学相应课程的教材或主要教学参考书。(5)每本列选的教材都须经过国内相应领域的资深专家审看和推荐。(6)教材的形式直接以英文原版形式印刷出版。

本系列教材将按分期分批的方式组织出版。为了便于使用本系列教材的相关教师和学生从学科和教学的角度对其在体系和内容上的特点和特色有所了解，在每本教材中都附有我们所约请的相关领域资深教授撰写的影印版序言。此外，出于多样化的考虑，对于某些基本类型的课程，我们还同时列选了多于一本的不同体系、不同风格和不同层次的教材，以供不同要求和不同学时的同类课程的选用。

本系列教材的读者对象为信息技术学科和电气工程学科所属各专业的本科生，同时兼顾其他工程学科专业的本科生或研究生。本系列教材，既可采用作为相应课程的教材或教学参考书，也可提供作为工作于各个技术领域的工程师和技术人员的自学读物。

组编这套国外知名大学原版系列教材是一个尝试。不管是书目确定的合理性，教材选择的恰当性，还是评论看法的确切性，都有待于通过使用和实践来检验。感谢使用本系列教材的广大教师和学生的支持。期望广大读者提出意见和建议。

Modern Control Systems Analysis & Design Using Matlab & Simulink

影 印 版 序

Robert H. Bishop 编著的“Modern Control Systems Analysis & Design: Using Matlab & Simulink”一书，属于和由 R. C. Dorf 和 R. H. Bishop 所编著的主教材“Modern Control Systems, 7th Edition.”相配套的一本辅助性教材。本书的目的是，引导学生在学习和掌握控制系统的分析和设计的基本理论和方法的同时，能将当前广为流行的现代计算工具 Matlab 和 Simulink 系统地和熟练地应用于控制系统的分析与设计中，包括对各类系统模型的建立、控制系统性能和稳定性的分析、各类控制系统的设计等，提供实际的示例和强化的训练。而这方面正是当前国内控制理论教学中所普遍欠缺的，因此本书的引进将会起到促进和借鉴的作用。

本书的 13 章内容与上述主教材的相应各章是相对应的。每章除有重点地简要归纳相应主题的主要理论和方法外，分别引入了 13 个取自于航天、航空、车辆、机械、医疗、电子等领域中具有实际背景的工程实例，诸如空间飞船、空间站、血压控制、飞机侧翼动力学、机器人控制摩托车、汽车速度控制、数字放音机带速控制等例子，其属性介乎于“原理例子”和“案例研究”之间。这种安排为学习如何运用现代计算工具来解决各种实际控制系统的分析与设计提供了范例，对于工科学生的控制系统分析和设计的深化学习和工程训练将会是大有益处的。

对于已经采用 R. C. Dorf 和 R. H. Bishop 编著的“Modern Control Systems, 7th Edition”一书作为教材的读者，这本辅助性教材无疑是一本具有重要参考价值的配套读物。就是对于没有采用上述教材的读者，本书也仍然是具有独立参考价值的一本好的辅助教材。这是因为，本书中所涉及的控制系统分析和设计的主要理论和方法几乎都见诸于大多数国内外的控制理论教材，而训练如何运用现代计算工具 Matlab 和 Simulink 来解决控制系统的分析和设计问题具有相对的独立性。特别是，相比于国内已出版的为数不多的同类教材，本书篇幅不大但实例众多，更为值得称道的是它突破了“就原理论述原理”的传统体系，显现出更多的工程性和趣味性，这对于提高工科大学生的学习兴趣和训练解决工程问题的能力将是非常有利的。

本书可作为控制工程、电机工程、电子工程、计算机工程、热能工程等各类专业的本科生学习控制理论基本课程的辅助教材，也可作为控制系统设计类课程的教材或参考教材，同时还可供想要了解和学习应用 Matlab 和 Simulink 等现代计算工具来分析和设计控制系统的广大工程师和技术人员作为自学和进修的读物。

郑大钟
清华大学自动化系
2003 年 2 月

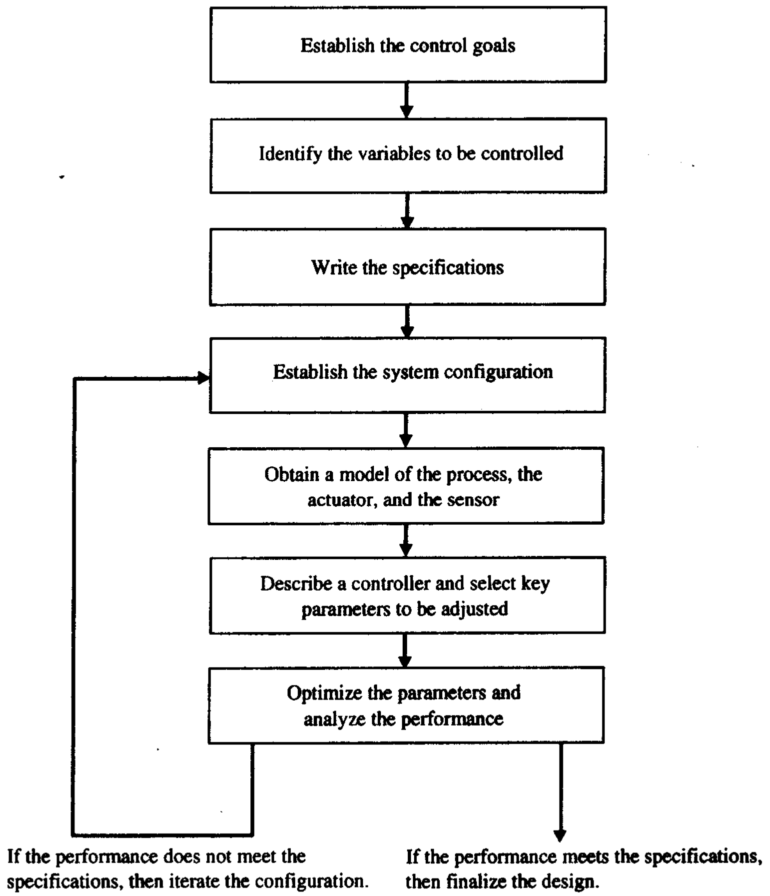
MODERN CONTROL SYSTEMS—THE SUPPLEMENT

This supplement is designed to be used as a companion to the main textbook, *Modern Control Systems* by Richard C. Dorf and Robert H. Bishop. The primary objective of this supplement is to strengthen the design emphasis by introducing a selected set of solved design problems. Each chapter focuses on one design problem adapted from *Modern Control Systems*. The problems are selected from a wide range of fields. In addition to the design problems, some chapters also include example problems that illustrate important points and concepts. Rather than focus just on the design issues of specific (and interesting) design problems, this supplement is built around the notion of a design process.

Design is the process of conceiving or inventing the forms, parts, and details of a system to achieve a reasoned purpose. Control system design is only one important example of design. Design is a creative endeavor, so there is not a unique methodology that guarantees a valid design solution. To help organize the design process, we suggest a series of steps leading to the final design. Every chapter addresses at least one step of the design process. In general, the early chapters focus on modeling, design specifications, and identification of important variables to be to controlled. The later chapters focus on controller selection and design and analysis of the controlled system. Of course the design process is inherently iterative, so some steps will be repeated as the design is refined. MATLAB and SIMULINK are valuable tools in the design process because they effectively assist in performing the repetitive steps quickly.

Now that powerful computers and software are available for control system design, some may ask the question, Why don't we program the full higher-order nonlinear equations, ignore all the modeling and analysis techniques, and use the computer to grind out an answer? There are many reasons why this is not a good way to solve an engineering problem. First, we do not get a feel for the problem. For example, suppose the team leader tells us the design specifications have been changed for the problem we are currently working. Which controller gain changes to meet the new design specifications? Do we need to change the controller structure? Without a feel for the problem, we may have few ideas on how to proceed. In this supplement we present the technique of obtaining approximate transfer function models to determine initial controller designs and then relying on MATLAB to fine-tune and analyze the closed-loop control system.

THE DESIGN PROCESS



In this manner, we can develop good engineering intuition regarding the design variables and how they affect the system response.

In this book we also use the notion of dominant poles to obtain initial control system designs. The idea is that we design the controller such that the closed-loop system response is dominated by certain poles placed appropriately to meet the design specifications. Again, we can use MATLAB to verify quickly that the design specifications have indeed been satisfied. Each time we use MATLAB in a problem solution in this supplement, we give the associated script. We can use the scripts to verify the results, but more importantly, they can be modified to solve other similar design problems.

To properly utilize this supplement it is essential to have access to *Modern Control Systems*. Many of the problems and examples in Dorf and Bishop are solved here using MATLAB and SIMULINK, but the background information presented in *Modern Control Systems* has not been repeated. For example, it is assumed that the reader is familiar with MATLAB. The main text *Modern Control Systems* contains relevant materials for new users of MATLAB and that material is not presented again in this supplement.

ORGANIZATION

Each chapter of the supplement follows the corresponding chapter in *Modern Control Systems*. To allow the reader to relate the supplement chapters to the main textbook chapters, the chapter titles have remained the same. However, we have added a subtitle indicating the primary design problem of that chapter.

- **Chapter 1: Introduction to Control Systems**
  A Space Shuttle Example
- **Chapter 2: Mathematical Models of Systems**
  Fluid Flow Modeling Example
- **Chapter 3: State Variable Models**
  A Space Station Example
- **Chapter 4: Feedback Control System Characteristics**
  Blood Pressure Control Example
- **Chapter 5: Performance of Feedback Control Systems**
  Airplane Lateral Dynamics Example
- **Chapter 6: Stability of Linear Feedback Systems**
  Robot-controlled Motorcycle Example
- **Chapter 7: Root Locus Method**
  Automobile Velocity Control Example
- **Chapter 8: Frequency Response Methods**
  Six-legged Ambler Example
- **Chapter 9: Stability in the Frequency Domain**
  Hot Ingot Robot Control Example
- **Chapter 10: Design of Feedback Control Systems**
  Milling Machine Control Example
- **Chapter 11: Design of State Variable Feedback Systems**
  Diesel Electric Locomotive Example
- **Chapter 12: Robust Control Systems**
  Digital Audio Tape Speed Control Example
- **Chapter 13: Digital Control Systems**
  Fly-by-wire Control Surface Example

The design problems in each chapter are all adapted from *Modern Control Systems*. In most cases, the problems are end-of-chapter problems revisited. The relationship between the chapter design problems in the supplement and *Modern Control Systems* is shown in the following table.

Supplement Chapter Number	Design Problem	Relationship to *Modern Control Systems*
1	Space Shuttle	P9.9
2	Fluid Flow Modeling	P2.12
3	Space Station Modeling	Section 3.9
4	Blood Pressure Control	AP4.5
5	Airplane Lateral Dynamics	DP5.1
6	Robot-controlled Motorcycle	DP6.6
7	Automobile Velocity Control	DP7.12
8	Six-legged Ambler	DP8.2
9	Hot Ingot Robot Control	DP9.10
10	Milling Machine Control	P10.36
11	Diesel Electric Locomotive	DP11.3
12	Digital Audio Tape Speed Control	DP12.2
13	Fly-by-wire Control Surface	AP13.2

THE SOFTWARE

It is assumed that the readers have access to MATLAB and the *Control System Toolbox*. All of the MATLAB examples in this supplement were developed and tested on a Power Macintosh 7200/90 with MATLAB Version 4.2c and the *Control System Toolbox*. Since it is not possible to verify each example on all the available computer platforms that are compatible with MATLAB, we restrict the computer topics covered in this supplement to those that are platform independent. It will be very helpful to have access to the MATLAB *Users Guide*.

Readers do not need access to SIMULINK to use this supplement effectively. Every design problem is solved using MATLAB, so skip the SIMULINK material if desired. It is clear, however, that SIMULINK provides valuable additional simulation capability; therefore, we introduce it in this supplement for those readers wishing to extend their knowledge base. We used SIMULINK 1.3c in the simulation development. It will be very helpful to also have access to the SIMULINK *Users Guide*.

A set of M-files, the *Modern Control Systems Supplement Toolbox*, have been developed by the author for this supplement. The M-files contain the scripts from each MATLAB example. You can retrieve the M-files from Addison-Wesley at **ftp.aw.com**. Please refer to the Addison-Wesley Computer Science and Engineering Web site at **http://www.aw.com/cseng** or call 1-800-322-1377 if you would like to purchase a copy of *Modern Control Systems*.

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OPEN LINES OF COMMUNICATION

The author and the staff at Addison-Wesley Publishing Company would like to establish an open line of communication with the users of this supplement. We encourage all readers to email Addison-Wesley with comments and suggestions for this and future editions. By doing this, we can keep you informed of any general interest news regarding the supplement and pass along interesting comments from other users.

Keep in touch!

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CONTENTS

CHAPTER 1

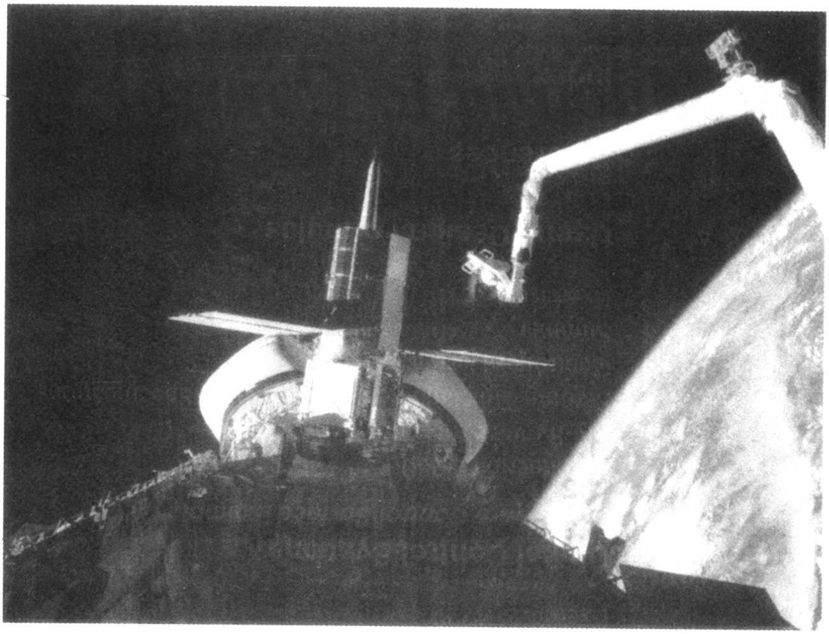
Introduction to Control Systems

A Space Shuttle Example

PREVIEW

This chapter provides an introduction to the control design process by describing a general approach to designing and analyzing a feedback control system. We discuss the basic components of control system design in the context of the process of design. We also discuss the notion of the design process used in all of the subsequent chapters. The idea is to emphasize the tight link between the theory and applications and the design process.

We introduce the simulation program SIMULINK in this chapter, which is an extension to MATLAB that enables students and practicing engineers to simulate dynamic systems quickly and effectively. Using block diagram windows, we can create and edit models by manipulating (principally with mouse-driven commands) model components, such as scopes, signal generators, and transfer functions. SIMULINK allows for graphical insight to a problem and helps to develop our intuition.



(Photo courtesy of NASA)

FIGURE 1.1
The space shuttle with the deployed Remote Manipulator System (RMS).

1.1 INTRODUCTION

Figure 1.1 shows the space shuttle during on-orbit operations with the robotic arm, known as the Remote Manipulator System (RMS). During shuttle capture and retrieve operations, the vehicle attitude hold control system is used to maneuver the vehicle to a desired attitude and to hold that attitude. The main components of the attitude hold control system are the primary reaction control system, the flight computer hosting the control algorithms, the astronaut piloting the vehicle (when not in attitude hold mode), the rotational hand controller, and the various sensors, such as rate gyros and accelerometers. A block diagram of the shuttle attitude hold control system is shown in Figure 1.2 [1]. Bear in mind that this block diagram is a simplification of the actual implemented control system on board the shuttle.

We can compare the shuttle controller block diagram shown in Figure 1.2 with a block diagram that is more characteristic of the ones found in most undergraduate controls textbooks. Most standard block diagrams have the form shown in the simplified block diagram in Figure 1.3. The following is a typical problem statement associated with the simplified block diagram (see for example P9.9 in *Modern Control Systems*):

Typical Problem Statement The key to future exploration and use of space is the reusable earth-to-orbit transport system, popularly known as the space shuttle. The shuttle carries large payloads into space and returns them to earth for reuse [2]. The block diagram of a pitch rate control system is shown in Figure 1.3. The sensor is represented by a gain,

$$H(s) = 0.5 ,$$

and the vehicle by the transfer function

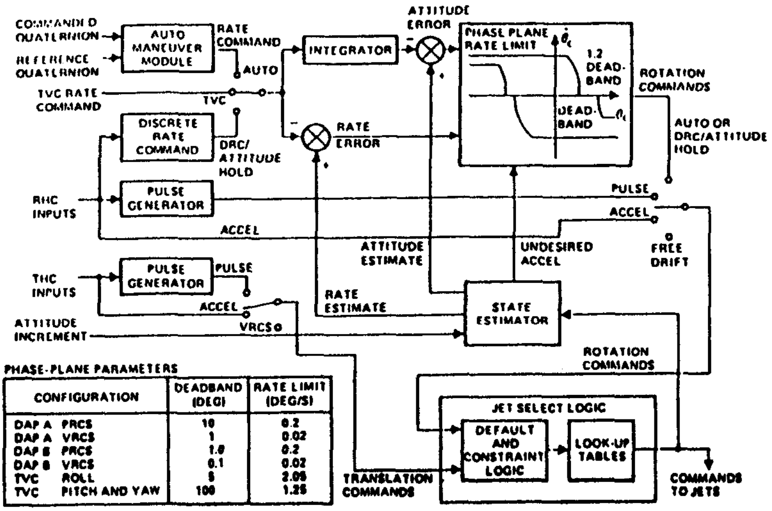
$$G(s) = \frac{0.3(s + 0.05)(s^2 + 1600)}{(s^2 + 0.05s + 16)(s + 70)} .$$

The controller can be a simple gain or any suitable transfer function. (a) Draw the Bode diagram of the system when $G_c(s) = s$ and determine the stability margin. (b) Draw the Bode diagram of the system when

$$G_c(s) = K_1 + \frac{K_2}{s} \quad \text{and} \quad \frac{K_2}{K_1} = 0.5 .$$

The gain K_1 should be selected so that the gain margin is 10 dB.

The space shuttle control system shown in Figure 1.2 has been replaced with



CONFIGURATION	DEADBAND (DEG)	RATE LIMIT (DEG/S)
DAP A PRCS	10	0.2
DAP A VRCS	1	0.02
DAP B PRCS	1.0	0.2
DAP B VRCS	0.1	0.02
TVC ROLL	5	2.05
TVC PITCH AND YAW	100	1.25

FIGURE 1.2
The space shuttle attitude hold control system.